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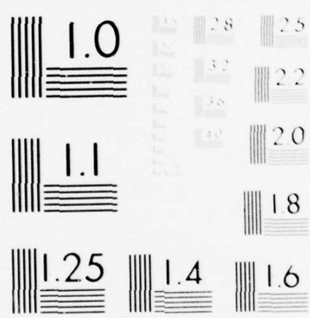
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U.S. ARMY MISSILE RESEARCH AND DEVELOPMENT COMMAND

STORAGE RELIABILITY

OF

MISSILE MATERIEL PROGRAM

ELECTRONIC VACUUM TUBE ANALYSIS

LC-78-VT1 JANUARY 1978

Redstone Arsenal, Alabama 35809

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This report documents findings on the non-operating reliability of vacuum tubes. A Weibull distribution is used to describe the failure distribution for high power tubes. This information is part of a research program being conducted by the U. S. Army R&D Command, Redstone Arsenal, Alabama.

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ELECTRONIC VACUUM TUBE ANALYSIS

LC-78-VT1 JANUARY 1978

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ABSTRACT

This report documents findings on the non-operating reliability of electronic vacuum tubes. Long term non-operating data has been analyzed and failure rate predictions have been developed for vacuum tubes.

This report is a result of a program whose objective is the development of non-operating (storage) reliability prediction and assurance techniques for missile materiel. The analysis results will be used by U. S. Army personnel and contractors in evaluating current missile programs and in the design of future missile systems.

The storage reliability research program consists of a country wide data survey and collection effort, accelerated testing, special test programs and development of a non-operating reliability data bank at the U. S. Army Missile Research & Development Command, Redstone Arsenal, Alabama. The Army plans a continuing effort to maintain the data bank and analysis reports.

This report is one of several issued on missile materiel. For more information contact:

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SECTION 1

INTRODUCTION

Materiel in the Army inventory must be designed, manufactured and packaged to withstand long periods of storage and "launch ready" non activated or dormant time. In addition to the stress of temperature soaks and aging, they must often endure the abuse of frequent transportation and handling, and the climatic extremes of the forward area battlefield environment. These requirements generate the need for special design, manufacturing and packaging product assurance and procedures. The U. S. Army Missile Command has initiated a research program to provide the required data and procedures.

This report is one of a series of reports on missile materiel. It covers findings from the research program on electronic vacuum tubes. The program approach on tubes included literature and users' surveys, data bank analyses, data collection from various military systems and special testing programs.

Storage failure rates have been developed for eight classes of electronic vacuum tubes. These failure rates were developed based on engineering and statistical analyses of available data.

SECTION 2

SUMMARY

Over 1.2 billion part hours with 404 failures were collected and analyzed. This represents information on over 77,000 tubes of different classes and characteristics from eight different sources.

Non-operational failure rate prediction models have been developed and are presented in Section 4.3. The models are based on a decreasing failure rate with storage time. Data indicates that vacuum tubes are failing early in storage and no significant increase in failures is indicated with time.

No difference was observed between the storage failure rates for pulsed and CW tubes. The data tends to indicate that the storage failure rate is independent of power and frequency characteristics.

The predominant storage failure rate is loss of vacuum. The predominant operational failure mode (wearout) does not seem to be a factor during storage.

SECTION 3

TUBE CLASSIFICATION AND FAILURE MODE ANALYSIS

3.1 Classification of Tubes

Data has been accumulated and analyzed on several types of tubes. A brief description of each type is included for the reader not familiar with these devices. Detailed descriptions and theory of operation for these tubes can be found in the referenced publications.

3.1.1 Magnetron

The magnetron is an oscillator which converts energy extracted from a constant electric field to an RF field. In its most basic configuration, it consists of a cathode, an anode, a set of straps and output couplings. The cathode is a heated cylindrical structure with the emitting surface all around it. The anode is a large block of copper, surrounding the cathode, in which slots and holes are cut. The straps are metal rings connected to alternate segments of the anode block to improve the stability and efficiency of the tube. A coupling loop in one of the cavities extracts the amplified RF energy.

There are several types of conventional magnetrons. The different names (strap and vane coaxial, rising sun, inverted coaxial, etc.) are due to the different configurations of the interaction region. However, they are all characterized by crossed electric and magnetic fields in the interaction region (hence the general name of "crossed field" amplifiers).

The principal advantages of the magnetron are relatively small size, light weight, reasonable operating voltages, good efficiency, and rugged construction. Its main disadvantage is that the magnetron, being an oscillator, is not suitable for use in coherent systems, or for generation of short high power pulses. Its spurious power levels are not the lowest.

3.1.2 Klystron

The Klystron is an amplifier characterized by high gain, high power, good efficiency, but relatively narrow bandwidths. Its high voltage requirements and large size limits its application in missile systems.

In general, a Klystron consists of a cathode, a modulating anode, an anode, RF cavities, RF input heater units and electron beam. The modulating anode located close to the cathode provides a means to pulse or modulate the electron beam by varying the applied voltage. The RF cavities serve as the anode since they are at a positive potential with respect to the cathode. Unlike most tubes, electrons are not collected by the anode but rather by the collector located at the far end of the tube. The input and output coupling loops are located in the first and last RF cavities respectively. The focusing magnets provide an axial magnetic field to counteract the mutual repulsion of electrons in the beam thus keeping it collimated.

High power tubes include X-ray radiation sheilds and a vac-ion pump to maintain the high vacuum required for proper operation.

3.1.3 Travelling Wave Tube

The travelling wave tube (TWT) is a thermionic tube characterized by high gain, large bandwidth, reasonable operating voltages but having low efficiency. The TWT is similar to the Klystron in both construction and principle of operation. It contains a cathode, an anode, input and output RF couplings and focusing magnets. Instead of RF cavities, the TWT contains a "slow wave structure" to accomplish velocity modulation of the beam. In low power tubes, the slow wave structure is a wire helix running axially along the tube. For higher power tubes heavier and more rugged structures capable of dissipating large amounts of heat are required. High power tubes also contain vac-ion pumps to maintain required vacuum.

A special case of the TWT is the Twystron (TWT/Klystron). This is a hybrid tube that essentially consists of a Klystron driving a TWT within a single bottle or enclosure. This arrangement combines the good efficiency and power of the Klystron with the large bandwidth capability of the TWT. For this analysis,

the Twystron has been included with the TWT's.

3.1.4 Amplitron, Sprytron

These are special cases of crossed field amplifiers. They are trademarks of private companies and represent modifications with special features of the classical crossed field amplifier.

3.1.5 Gridded Tubes

These represent a class of grid-controlled tubes. Although capable of large amounts of power, gridded tubes are constrained to the lower frequencies. In general they represent older technology since most modern microwave applications have been taken over by other tubes. Their high frequency constraints limit this application in missiles. However, for the sake of completeness, this data has been included.

3.2 Failure Mode Analysis

The failure mode analysis is based on a population of over 12,000 tubes, 484 of which failed during storage. Although detailed failure reports were not available on any of the tubes, cause of failure was recorded in most cases. The total number of failures in the population of 12,000 tubes was over 600, however many of these were system related failures and were not counted as tube failures. In some instances, external waveguides arced causing a surge of current which ultimately damaged the tube. Other examples of system related failures were cooling system, high VSWR in the system, heat exchanger, improper output coupling failures, and others. All of these resulted in malfunction as soon as the tube was installed and power applied to it. However, they did not represent intrinsic tube failures and were disregarded in the analysis.

The distribution of tube failures is shown in Figure 3-1. The key to the horizontal axis in Figure 3-1 is shown in Table 3-1. The "%" column represents the percentage of all failures in which a specific mode was observed.

The predominant storage failure mode is gassy, loss of vacuum. This mode represents 38% of all the failures and it was observed three times as many as the second (internal short) most frequent one. When tubes have been in storage without

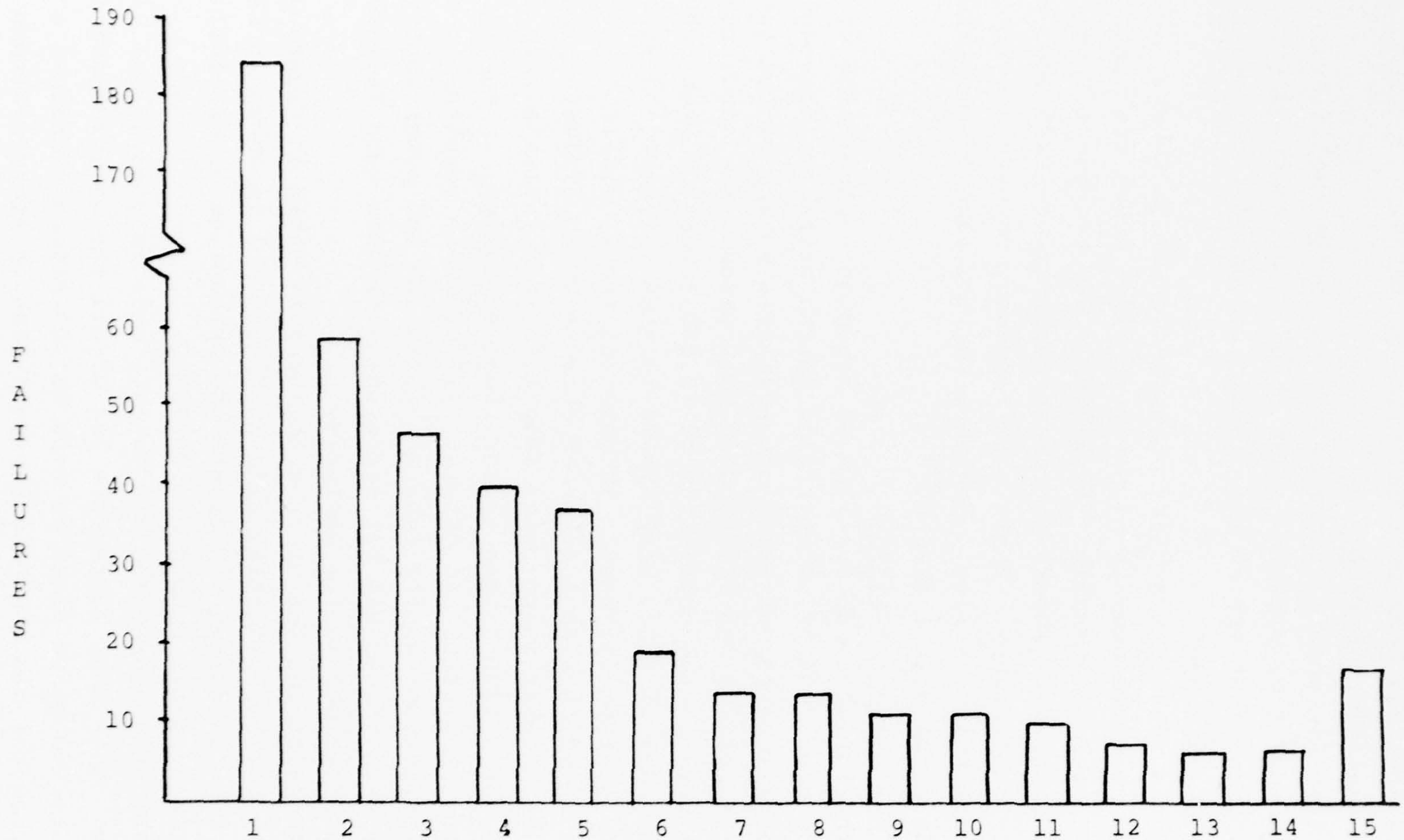


FIGURE 3-1. DISTRIBUTION OF FAILURE MODES

TABLE 3-1. FAILURE MODE DISTRIBUTION & PERCENTAGE

FAILURE MODE IDENTIFICATION NUMBER	FAILURE MODE	%
1	Gassy, loss of vacuum	38.0
2	Internal short	12.2
3	Undetermined	9.7
4	Open filament	8.3
5	Handling/packaging	7.6
6	Heater short	3.9
7	Tuning mechanism/mechanical failure	2.9
8	Low emission	2.9
9	High gas pressure/high ion pump current	2.3
10	Coolant leak within tube	2.3
11	Internal arcing	2.1
12	Filament failure	1.4
13	Poor spectrum	1.2
14	Cathode depletion	1.2
15	Others	4.0
	Window failures	
	Low power output	
	Failed min. gain check	
	Tuner failure	
	Excessive tuner torque	
	Focus coil failure	

power applied to them, gases either form within the tube or leak in through seals resulting in loss of vacuum. If power is applied suddenly, the gases ionize and become a conducing media drawing large amounts of current which, if sustained, will burn out the tube. This failure mode was not only predominant in the entire population of tubes but it was also dominant within each tube category except gridded tubes.

Loss of vacuum during prolonged storage is often the result of a microscopic leak in the tube envelope. As the tube skin area and the number of vacuum tight joints increase so does the potential for a leak. In an effort to reduce potential loss of vacuum, the porosity of metals employed should be seriously considered. Small quantities of undesirable gases can also originate from the various metallic surfaces within the vacuum.

Although it was the predominant mode for storage conditions, loss of vacuum is seldom observed during operation. The reason is that while small amounts of gases can leak in while the tube is operating, they are burned as they form and seldom reach high enough concentrations to form arcs.

Internal short was the second highest failure mode. However, over 54% of the failures caused by internal shorts happened in gridded tubes. These were mainly shorts in the delicate grid structure. In tubes other than grid controlled this mode was responsible for only 6% of the failures. Since gridded tubes are not widely used in modern missiles, internal short is not as predominant as shown in Table 3-1.

The third most frequent reported mode was "undetermined." These were cases where no failure analysis was made or where it was impossible to determine the actual cause for the failure.

Open filament was reported 8.3% of the time. When combined with heater shorts (3.9%) and undetermined filament failures (1.4%), heater associated failures accounted for 13.6% of the failures. Corrosion and embrittlement of the delicate filament structure with time may account for a large number of these failures.

Handling and packaging accounted for 7.6% of the failures. This is a general category with a wide variety of interpretations the possibilities including dropping a tube resulting in major mechanical damage. Due to the lack of further identification failures attributed to handling and packaging were not included in failure rate computations.

Tuning mechanism failures occurred mostly on mechanically tuned magnetrons. This problem did not occur in TWTs and only a few times in Klystrons. Mechanical tuning is used mostly in

high power magnetrons. Small tubes used in missile applications are mostly electronically or voltage tuned. Therefore, this failure mode is not severe in missile environments.

Low emission is usually the predominant operational failure mode. It indicates cathode wearout. As a storage mode it may indicate oxidation of the cathode surface caused by small amounts of moisture trapped within the tube.

The balance of the failures were due to a variety of failure modes none of which represents a major storage associated problem.

3.3 Product Assurance Measures

As shown in Section 3.2 , the principal storage associated problem is loss of vacuum. This problem can be alleviated with a combination of manufacturing control, proper storage and handling procedures, and tube preparation before full operation.

During manufacturing gases can be trapped within the tube enclosure. To minimize this, tubes should be assembled in a hard vacuum atmosphere. Vacuum seal areas should be minimized and special attention should be given to selection and application of sealant material. The porosity of the materials should be strictly controlled to avoid gas leaks through microscopic pores.

During storage, humidity control is important to avoid corrosion of metal parts of the tube. If the tube is equipped with a vac-ion pump, the pump should be operated periodically to extract any gases accumulated during storage. The pump should be operated every time after transportation and before operation. All tubes, especially grid controlled tubes, should be protected from extreme or continuous shock and vibration.

If a gassy tube is powered suddenly, the trapped gas will ionize causing arcing and tube damage. However, if power is applied gradually, the gas will burn out slowly without arcing. Therefore "conditioning" of the tube by gradual application of power will minimize the problem. This is a normal process in high power radar tubes, however it may not always be possible on a missile resting in the launcher and which must be readied and launched in a matter of seconds. However, this procedure must be followed whenever a tube has been in storage for some

time and is being readied to install in a missile. The conditioning process should include as a minimum slow heater warm-up; anode, cathode, and helix conditioning by applying high voltage gradually; and RF conditioning by applying RF drive gradually to maixmum power level and pulse width.

SECTION 4

NON-OPERATING DATA ANALYSIS

The information in this section is based on data collected on over 77,000 tubes of eight types with combined storage hours of over 1.2 billion and 404 failures.

4.1 Tube Non-Operating Data

Available data on the different types of tubes is summarized in Table 4-1. The information in Table 4-1 does not constitute all of the data collected. Several hundred thousand hours and over 150 failures were immediately disqualified because they were either system failures or the result of mishandling.

Data was obtained from eight sources. Source A represents a reliability study performed under contract to RADC. This source identified the type and quality grades for the devices, however, it provided no information regarding storage conditions or intervals. For vacuum tubes, one entry on Sprytron tubes with 400 thousand storage hours and no failures and one entry on MIL-STD tubes with 1 million storage hours and 14 failures were recorded.

Source B represents data from orbiting spacecraft. Eighteen TWTs were in a standby (non-operating) mode and all 18 operated without failure when turned on.

Source F represents missile storage between 1963 and 1965. The missiles were subjected to periodic checkout. Storage intervals ranged from 2 to 29 months. Cumulative operating time on the tubes was from 1 to 20 hours. Four TWT failures were reported with the following failure modes: Moding at start of oscillation (Age - 5 months); Spectrum too wide (Age - 8 months); Arcing (Age - 15 months); and Vibration (Age - 12 months). One magnetron failure was recorded at age 5 months - failure mode - excessive helix current.

Source G represents shelf storage between 1970 and 1972 of large TWT's (peak power - 200 KW). Storage intervals ranged from 6 to 22 months. The devices were conditioned after storage before turn-on. No failures were recorded.

TABLE 4-1. VACUUM TUBE NON-OPERATING DATA

DATA ENTRY NO.	SOURCE	TUBE TYPE	NO. OF UNITS	STORAGE INTERVAL (MONTHS) MIN.	AVE.	MAX.	NO. FAILED	STORAGE HRS. x 10^6	λ IN FITS
1	A	Sprytron (Hi-Rel)	-	-	-	-	0	.410	<2439.
2		Tubes (MIL-STD)	-	-	-	-	14	1.017	13766.
3	B	TWT	18	-	20	-	0	.266	<3159.
4	F	Magnetron	124	2	7	29	4	.624	6410.
5		TWT	124	2	7	29	1	.624	1663.
6	G	TWT	25	-	18	-	0	.320	3121.
7	Missile E-1	Klystron	874	-	20	-	1	12.760	78.
8		Recng Tubes (JAN)	67298	-	20	-	12	982.552	12.
9	H	Twystron	77	1	27	68	2	1.508	1326.
10		Twystron	12	2	15	26	6	.134	44776.
11		TWT	355	1	11	70	9	2.889	3115.
12		TWT	13	1	9	33	0	.090	<11111.
13		TWT	12	1	12	16	1	.101	9901.
14		Klystron, Pulsed	358	1	37	106	28	9.605	2915.
15		Klystron, Pulsed	103	2	28	99	4	2.089	1915.
16		Klystron, Pulsed	275	1	26	153	18	5.248	3430.
17		Klystron, Pulsed	109	1	20	111	10	1.580	5329.

TABLE 4-1. VACUUM TUBE NON-OPERATING DATA (cont'd)

DATA ENTRY NO.	SOURCE	TUBE TYPE	NO. OF UNITS	STORAGE INTERVAL (MONTHS) MIN.	AVE.	MAX.	NO. FAILED	STORAGE HRS. x 10^6	λ IN FITS
18	H	Klystron, Pulsed	102	1	13	99	5	.970	5155.
19		Klystron, Pulsed	452	1	20	116	18	6.576	2737.
20		Klystron, Pulsed	300	1	9	46	7	1.906	3673.
21		Klystron, Pulsed	19	1	12	40	1	.164	6098.
22		Klystron, Pulsed	14	1	79	157	0	.807	<1239.
23		Klystron, CW	29	1	7	24	1	.152	6579.
24		Klystron, CW	253	1	12	85	6	2.138	2806.
25		Klystron, CW	45	1	14	49	4	.467	8565.
26		Klystron, CW	22	5	88	160	2	1.416	1412.
27		Klystron, CW	58	1	7	26	6	.280	21429.
28		Klystron, CW	12	4	18	43	1	.154	6494.
29		Klystron, CW	3	38	61	76	1	.134	7463.
30		Klystron, CW	3	6	19	26	0	.041	<24390.
31		Klystron, CW	130	1	9	104	13	.858	15152.

TABLE 4-1. VACUUM TUBE NON-OPERATING DATA (cont'd)

DATA ENTRY NO.	SOURCE	TUBE TYPE	NO. OF UNITS	STORAGE INTERVAL (MONTHS) MIN.	AVE.	MAX.	NO. FAILED	STORAGE HRS. x 10^6	λ IN FITS
32	H	Klystron, CW	30	1	9	46	0	.196	<5102.
33		Klystron, CW	4	8	22	60	0	.064	<15625.
34		Klystron, CW	2	28	32	35	0	.046	<21739.
35		Klystron, CW	5	1	5	9	0	.018	<55555.
36		Klystron, CW	82	1	15	92	2	.906	2208.
37		Klystron, CW	21	6	88	180	0	1.355	<738.
38		Klystron, CW	54	1	19	83	0	.742	<1348.
39		Klystron, CW	2	11	16	20	0	.023	<43478.
40		Klystron, CW	5	36	60	85	0	.219	<4566.
41		Klystron, CW	71	1	26	103	0	1.341	<746.
42		Klystron, CW	54	1	12	55	3	.465	6452.
43		Klystron, CW	301	1	15	132	9	3.201	2812.
44		Klystron, CW	18	3	20	59	2	.261	7663.
45		Klystron, CW	16	1	25	71	2	.288	6944.

TABLE 4-1. VACUUM TUBE NON-OPERATING DATA (cont'd)

DATA ENTRY NO.	SOURCE	TUBE TYPE	NO. OF UNITS	STORAGE INTERVAL (MONTHS) MIN.	AVE.	MAX.	NO. FAILED	STORAGE HRS. x 10^6	λ IN FITS
46	H	Magnetron	2592	1	78	221	116	136.568	849.
47		Magnetron	211	1	23	240	12	3.497	3432.
48		Magnetron	374	1	28	189	13	7.746	1678.
49		Magnetron	261	1	11	74	6	2.144	2799.
50		Magnetron	293	1	10	53	3	2.233	1343.
51		Magnetron	10	3	13	23	1	.091	10989.
52		Magnetron	10	1	10	66	1	.071	14085.
53		Magnetron	244	1	11	53	2	2.011	995.
54		Magnetron	117	1	11	74	2	.969	2064.
55		Magnetron	49	1	12	43	3	.431	6961.
56		Magnetron	9	2	17	66	0	.114	<8772.
57		Gridded Tube	285	1	11	75	10	2.359	4239.
58		Gridded Tube	138	1	13	53	11	1.284	8567.
59		Gridded Tube	356	1	12	78	17	3.119	5450.
60		Amplitron	145	1	19	88	13	1.970	6599.
61	Missile D	Gridded Tube	159	1	17	62	0	1.936	<517.

Missile E-1 data represents 874 missiles stored for 20 months during 1967 and 1968. The missiles were stored in containers exposed to external environmental conditions in the northeast U. S. They were also transported from coast to coast. No tests were performed until the end of the 20 months. The data included nearly 13 million klystron storage hours with one failure recorded as "open." In addition, one billion storage hours were recorded for receiving tubes with 13 failures recorded. The failures were listed as defective (3); shorts (5); opens (2); low gain (1), open heaters (2).

Source H represents shelf storage data on high power devices. Table 4-2 lists the tube type and power ratings. Data was not available on which tubes may have been preconditioned upon removal from storage.

Missile D data represents 159 missiles stored for periods from one month up to 62 months for an average storage period of 17 months. The missile storage was environmentally controlled and periodic checkouts were performed. The data includes nearly two million storage hours for the triode cavity oscillator with no failures recorded.

TABLE 4-2. SOURCE H TUBE TYPES

TUBE TYPE	DATA ENTRY NO.	TUBE TYPE NO.	POWER PEAK	POWER AVE.	FREQ. (MHz)
Twystron	9	VA913A	5 MW	10 KW	5500
	10	VA145E	3 MW	5 KW	3000
TWT	11	ZM3167	5 KW	10 W	5600
	12	VA138D	-	70 W	420
	13	VA643	Class.	Class.	Class.
Klystron, Pulsed	14	L3403	1.3 MW	75 KW	400
	15	VA842	1.3 MW	75 KW	400
	16	L3035	2.2 MW	7 KW	1300
	17	L3250	10 MW	15 KW	1300
	18	Z5010A	10 MW	15 KW	1300
	19	5AC42A	3 MW	6 KW	5600
	20	ZM3038A	15 MW	30 KW	2500
	21	X780D	2.5 MW	75 KW	1300
	22	4KMP1000LF	470 MW	4.6 KW	600
Klystron, CW	23	VA853	-	75 KW	900
	24	3KM5000PA	-	20 KW	330
	25	3KM5000PA2	-	23 KW	330
	26	3KM3000LA	-	100 KW	400
	27	VA888E	-	1 KW	4700
	28	3KM300LA	-	100 KW	400
	29	4KM50LB	-	14 KW	410
	30	4KM17000LA	-	75 KW	410
	31	3KR1000LQ	-	76 KW	870
	32	4KM50000LQ	-	11 KW	800
	33	4KM50SJ	-	12 KW	2100
	34	4KM50LC	-	14 KW	400
	35	3K5000LA	-	10 KW	500
	36	310M50000PA1	-	23 KW	330
	37	3K30000LQ	-	2 KW	800
	38	4KM3000LR	-	2 KW	800
	39	VA800E	-	10 KW	2100
	40	VA856B	-	2 KW	7600
	41	4K50000LQ	-	10 KW	800
	42	4KM50SK	-	12 KW	2600
	43	4KM50000LR	-	12 KW	870
	44	4K3CC	-	2 KW	800
	45	4K3JK	-	1 KW	2600
Magnetron	46	QK338A	4.5 MW	4.5 KW	2800
	47	QK6410	4.5 MW	4.5 KW	2800
	48	QK327A	4.5 MW	2.5 KW	2800
	49	8798	450 KW	450 W	2800
	50	7256	40 KW	40 W	9100
	51	400615	1 MW	1 KW	1300
	52	5586	800 KW	400 W	2800

TABLE 4-2. SOURCE H TUBE TYPES (cont'd)

TUBE TYPE	DATA ENTRY NO.	TUBE TYPE NO.	POWER PEAK	POWER AVE.	FREQ. (MHz)
Magnetron	53	7256	40 KW	40 W	9100
	54	8798M	450 KW	450 W	2800
	55	8798F	450 KW	450 W	2800
	56	5586	800 KW	400 W	2800
Gridded Tubes	57	2041	300 KW	3 KW	430
	58	7835	10 MW	60 KW	450
	59	6952	224 KW	4 KW	430
Amplitron	60	QK681	Class.	Class.	Class.

4.2 Data Analysis

4.2.1 Low Power Tubes

Four sources contain data which can be directly related to missile applications. These are relatively small, low powered devices. Table 4-3 summarizes this data.

TABLE 4-3. VACUUM TUBE DATA - MISSILE APPLICATIONS

SOURCE	TUBE TYPE	AVE. AGE	NON-OP. HRS. x 10^6	FAIL-URES	λ IN FITS	90% ONE-SIDED CONF. LIMIT λ IN FITS
F	Magnetron	7	.624	4	6410.	12821
B & F	TWT	8.6	.890	1	1124.	4372
Missile E-1	Klystron	20.	12.760	1	78.	305
Missile E-1	Recng. Tubes	80.	982.552	12	12.	55.
Missile D	Gridded Tube	16.7	1.936	0	<517.	1193.

4.2.2 High Power Tubes

Sources G and H represent relatively large vacuum tubes, some of which might be applicable to missile environments. The initial analysis divided the data by types and statistically tested whether the individual entries could be combined into single data sets. Next, the data entries were time lined to attempt to measure the effect of storage time on the failure rate. The analysis indicated a significant decrease in failure rate with storage length. This suggested that the devices were failing very early in storage and no significant increase in failure occurred as time increased. An attempt was made to fit the Weibull failure distribution to this data in the form:

$$\lambda(t) = e^{(\beta-1)\text{Ln}t - \text{Ln}\alpha}$$

where $\lambda(t)$ is the hazard rate or instantaneous failure rate per billion hours.

β = shape parameter

α = scale parameter

t = storage hours in billions

A fairly high correlation was made to this function, with the β (shape) parameter less than one, again suggesting that the majority of the failures were occurring early in storage. The individual analyses for the various tube types are presented below:

4.2.2 TWT's

Data entries 6, 9, 10, 11, 12 and 13 were combined in the TWT analysis. Note that twystrons are included in this category. All six data entries were tested to determine if a single failure rate applicable to the general category of TWT's could be developed. The test indicated that the failure rate for data entry 10 is significantly different from the remaining devices. No direct correlation to power or frequency could be made to this difference in failure rate. Table 4-4 summarizes the TWT data.

TABLE 4-4. TWT FAILURE RATE DATA SUMMARY

ENTRY NOS.	HRS. $\times 10^6$	FAILURES	λ IN FITS	90% UPPER CONF. LIMIT λ IN FITS	AVG. AGE
6,9,11,12, 13	4.908	12	2445.	3632	14 mos.
10	.134	6	44776.	78720	15 mos.

From inspection of the data, it was evident that a decrease in failure rate occurs from 6 months on. This suggests that the majority of failures are occurring early in storage. Therefore, whether the tubes are tested at six months or at 60 months, the same approximate percent of failures will be discovered.

To obtain a distribution of these failures, the data was sorted by age into groups of approximately 80 units each for entries 6, 9, 11, 12, 13 and 3 units each for entry 10. Tables 4-5 and 4-6 show this data grouping.

TABLE 4-5. TWT (entries 6, 9, 11, 12 & 13) GROUPING OF DATA BY AGE

STORAGE INTERVAL	AVERAGE AGE	UNITS	FAIL-URES	MILLION HOURS	ACTUAL λ IN FITS	PREDICTED λ IN FITS
1-2 mo.	1.4 mo.	79	1	.0796	12563	12563
3-5 mo.	3.6 mo.	74	3	.1949	15393	6572
6-9 mo.	7.3 mo.	87	2	.4679	4274	4047
10-17 mo.	13.0 mo.	84	2	.7994	2502	2724
18-24 mo.	19.6 mo.	76	1	1.0877	919	2055
25-70 mo.	38.8 mo.	82	3	2.3229	1291	1286

$$\lambda(t) = e^{(0.314-1)\mathrm{Ln}t - \mathrm{Ln}(1.0243)}$$

Index of Correlation = 0.77

t = Storage time in billion hours

TABLE 4-6. TWT (entry 10) GROUPING OF DATA BY AGE

STORAGE INTERVAL	AVERAGE AGE	UNITS	FAIL-URES	MILLION HOURS	ACTUAL λ IN FITS	PREDICTED λ IN FITS
2-4 mo.	3.0 mo.	3	2	.0066	303030	196742
5-18 mo.	11.7 mo.	3	1	.0256	39063	55265
19-24 mo.	21.3 mo.	3	1	.0467	21413	31452
25-26 mo.	25.3 mo.	3	2	.0555	36036	26755

$$\lambda(t) = e^{(.063-1)\mathrm{Ln}t - \mathrm{Ln}(1.0168)}$$

Index of Correlation = .89

t = storage time in billion hours

A Weibull distribution was fit to the data and a fair correlation with the field data was obtained. The resulting functions and correlation factors are shown in Tables 4-5 and 4-6.

Figures 4-1 and 4-2 present a graph of the function and the individual data points.

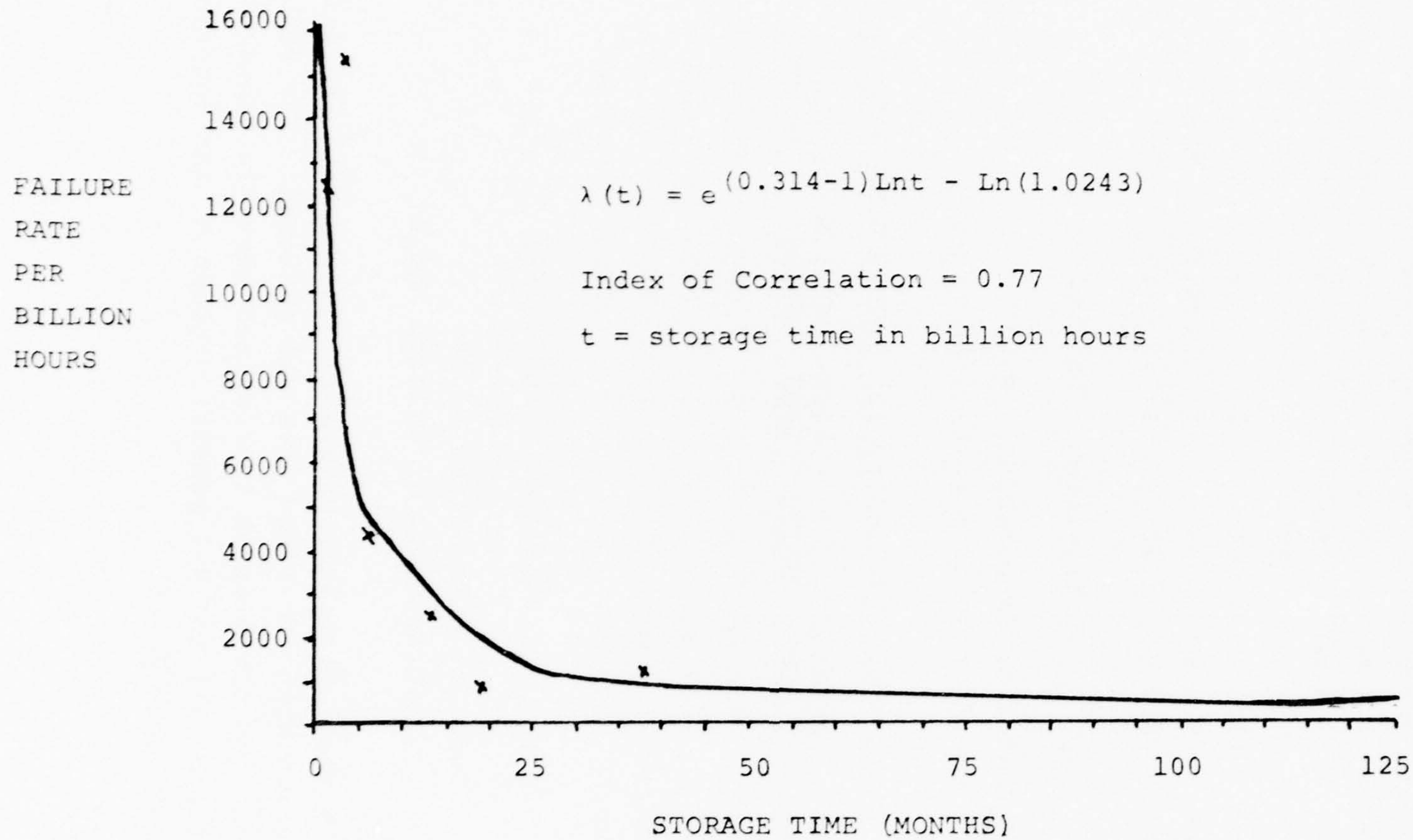


FIGURE 4-1. TWT (ENTRIES 6, 9, 11, 12 & 13) FAILURE RATE MODEL

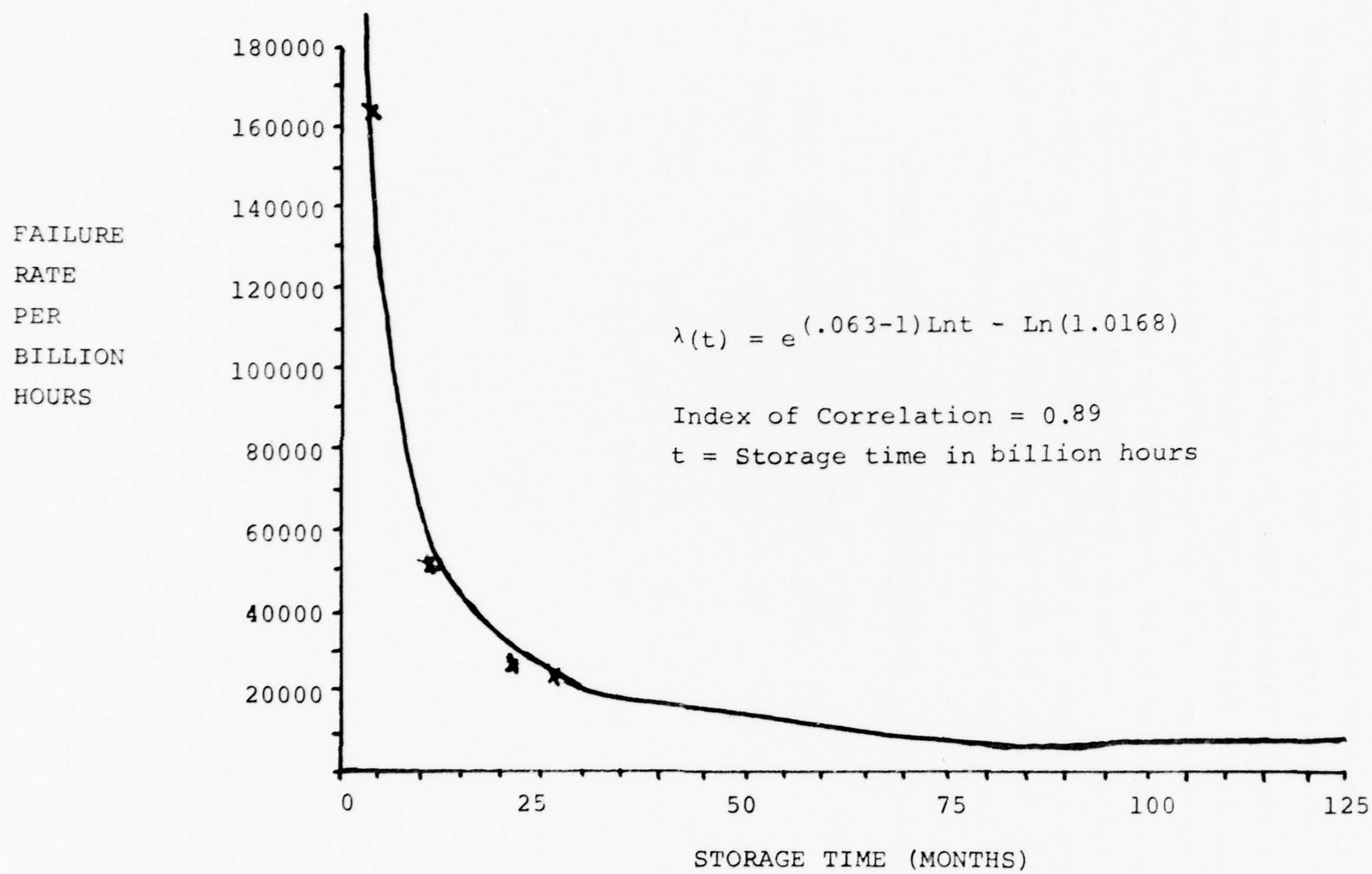


FIGURE 4-2. TWT (ENTRY 10) FAILURE RATE MODEL

4.2.2.2 KLYSTRONS

Data entries 14 through 22 represent pulsed Klystrons and entries 23 through 45 represent continuous wave Klystrons. Within these two groupings, the entries were tested to determine whether a single failure rate is applicable. For the pulsed Klystrons, it is possible for all entries to be from the same failure population. For the continuous wave Klystrons, entries 27 and 31, appears to be statistically different from the remaining entries. Table 4-7 summarizes this data. Testing of the pulsed Klystron data with the continuous wave Klystron data (excluding entries 27 and 31) indicated that it is possible for all the entries to have the same failure population.

TABLE 4-7. KLYSTRON FAILURE RATE DATA SUMMARY

ENTRY. NOS.	HRS. x 10^6	FAILURES	λ IN FITS	90% UPPER CONF. LIMIT λ IN FITS	TYPE	AVG. AGE
14 thru 22	28.945	91	3144	3608	pulsed	19 mos.
23 thru 26, 28 thru 30, & 32 thru 45	13.627	33	2422	3058	contin. wave	28 mos.
27 and 31	1.138	19	16696	22765	contin. wave	8 mos.
14 thru 26 28 thru 30 & 32 thru 45	42.572	124	2913	3276	pulsed & contin. wave	21 mos.

Again, inspection of the Klystron data on a time line, indicated that the failure rate was decreasing with time. The data was sorted by age into groups of approximately 260 units each. Tests within these groups indicated that the failure distribution for entries 27 and 31 were not different from the other entries. The average age of the devices in the combined data were shorter when tested resulting in a higher failure rate of the total entry. An attempt to fit a Weibull distribution to this data was made and shown in Table 4-8 with fair correlation. Figure 4-3 presents a graph of the function and the individual data points.

TABLE 4-8. KLYSTRON GROUPINGS BY AGE

STORAGE INTERVAL	AVG. AGE.	UNITS	FAIL-URES	HOURS	ACTUAL λ IN FITS	PREDICTED λ IN FITS
1-2 mo.	1.2 mo.	396	15	.4154	36110	23241
3-4 mo.	3.5 mo.	306	12	.7767	15450	12183
5-6 mo.	5.6 mo.	287	12	1.1658	10293	8639
7-8 mo.	7.5 mo.	210	5	1.1154	4483	7101
9-11 mo.	9.9 mo.	255	10	1.8476	5412	5659
12-14 mo.	12.9 mo.	247	8	2.3178	3452	4684
15-19 mo.	16.9 mo.	237	11	2.9229	3763	3836
20-26 mo.	23.1 mo.	252	13	4.2413	3065	3056
27-38 mo.	32.0 mo.	263	23	6.1517	3739	2403
39-55 mo.	45.7 mo.	249	14	8.3074	1685	1853
56-180 mo.	79.3 mo.	250	20	14.4679	1382	1239

$$\lambda\ (t) = e^{(.269-1)\mathrm{Lnt}\ -\ \mathrm{Ln}(1.0106)}$$

Index of Correlation ≈ 0.90

t = Storage time in billion hours

4.2.3 MAGNETRONS

Data entries 46 through 55 represent Magnetrons. Testing these entries indicated three distinct groups of failure population (Table 4-9): entries 46 and 53 with a combined failure rate of 961 fits; entries 47 thru 50, 54 and 56 with a combined failure rate of 2685 fits, and entries 51, 52, and 55 with a combined failure rate of 15760 fits. No correlation to size or frequency could be made to these failure rate differences.

As with the TWTs and Klystrons, the magnetrons exhibited a decreasing failure rate with time. The data was sorted by age into groups of approximately 320 units each. Tests within these groups indicated no difference in the failure populations for all Magnetron entries. The data is shown in Table 4-10. The Weibull function of the storage time was fit to the data with fair correlation. Figure 4-4 presents a graph of the function and the individual data points.

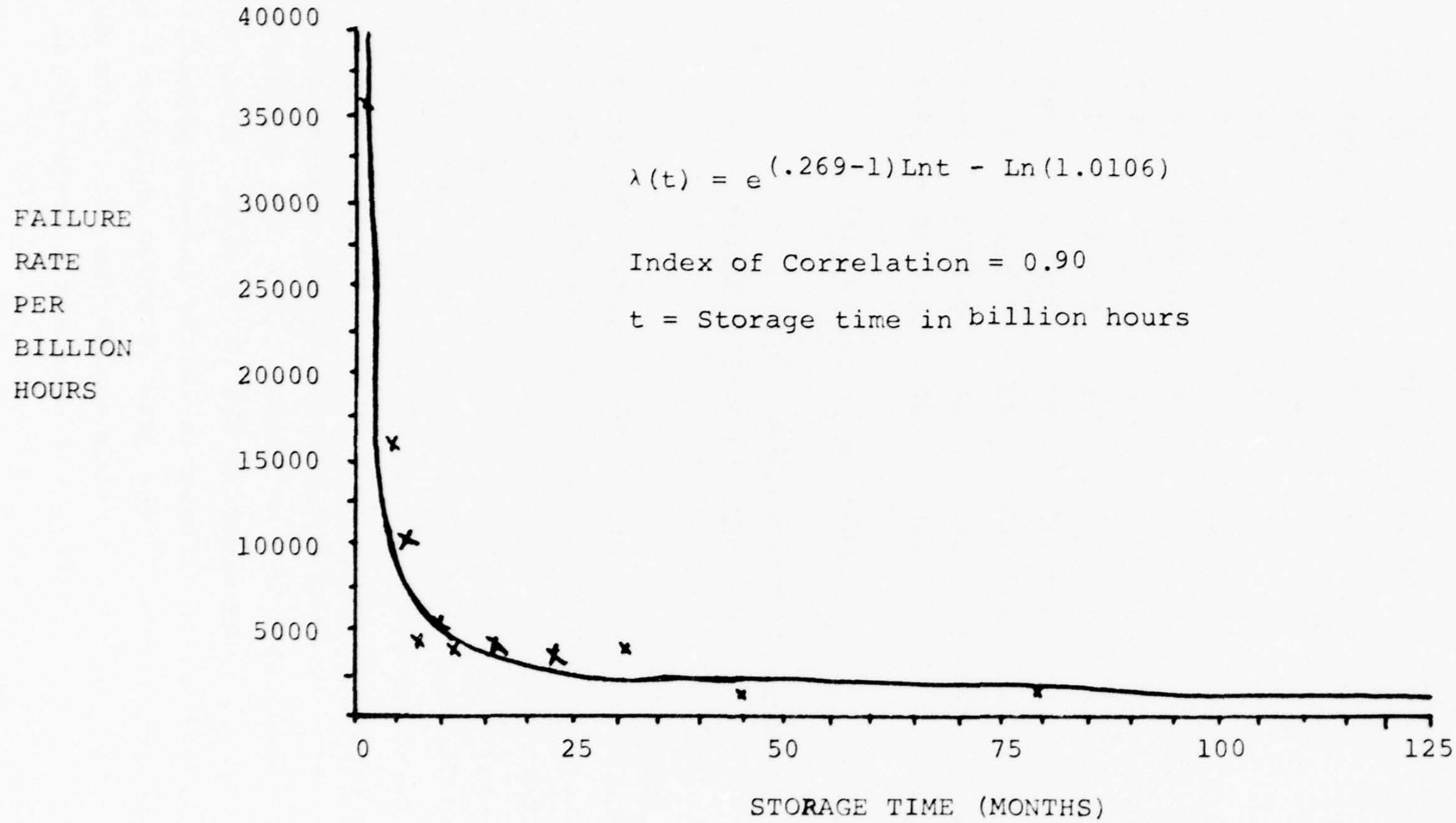


FIGURE 4-3. KLYSTRON FAILURE RATE MODEL

TABLE 4-9. MAGNETRON FAILURE RATE DATA SUMMARY

ENTRY NO.	HRS. x 10^6	FAILURES	λ IN FITS	90% UPPER CONF. LIMIT λ IN FITS	AVG. AGE
46 & 53	13.579	118	851	961	67 mos.
47,48,49, 50,54,56	16.703	36	2155	2685	18 mos.
51,52,55	.593	5	8432	15760	12 mos.

TABLE 4-10. MAGNETRON GROUPINGS BY AGE

STORAGE INTERVAL	AVG. AGE	UNITS	FAILURES	HOURS	ACTUAL λ IN FITS	PREDICTED λ IN FITS
1-3 mo.	2.40	305	6	.4373	13721	10284
4-6 mo.	5.2	344	12	1.3052	9194	5256
7-9 mo.	8.1	292	9	1.7286	5207	3866
10-14 mo.	12.0	372	18	3.2040	5618	2985
15-19 mo.	16.9	328	10	4.0354	2478	2334
20-26 mo.	24.0	298	21	5.2136	4028	1831
27-49 mo.	36.1	324	18	8.5468	2106	1379
50-75 mo.	67.9	317	4	15.7645	255	890
76-84 mo.	80.4	320	13	18.7844	692	794
85-92 mo.	88.5	301	5	19.4538	257	743
93-99 mo.	95.8	324	8	22.6475	353	704
100-111 mo.	105.1	330	15	25.3208	592	660
112-240 mo.	127.4	315	20	29.2978	683	578

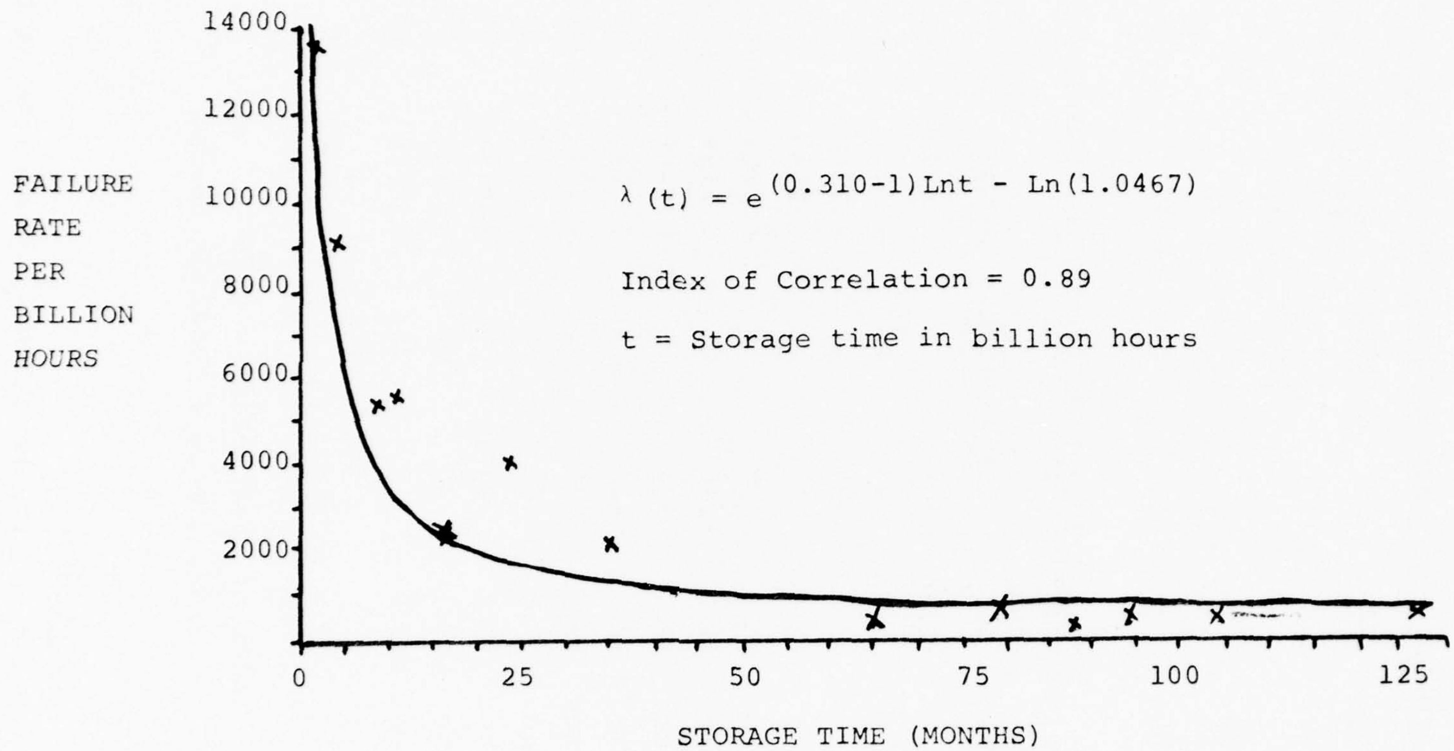
$$\lambda(t) = e^{(0.310-1)\text{Ln}t - \text{Ln}(1.0467)}$$

Index of Correlation = 0.89

t = Storage time in billion hours

4.2.2.4 GRIDDED TUBES

The data on gridded tubes is summarized in Table 4-11. Statistical test indicate no distinct difference in the failure rate of the three data entries.



$\lambda(t) = e^{(0.310-1)\mathrm{Ln}t - \mathrm{Ln}(1.0467)}$

Index of Correlation = 0.89

t = Storage time in billion hours

FIGURE 4-4. MAGNETRON FAILURE RATE MODEL

The failure data was sorted by age into groups of approximately 70 units showing an apparent decrease in failure rate with time. The Weibull function of the storage time was fit to the failure rate data with an index of correlation equal to 0.85 as shown in Table 4-12. Figure 4-5 presents a graph of the function with the data points.

TABLE 4-11. GRIDDED TUBES FAILURE RATE DATA SUMMARY

ENTRY NOS.	HRS. x 10^6	FAILURES	λ IN FITS	90% UPPER CONF. LIMIT λ IN FITS	AVG. AGE
57,58,59	6.762	38	5620	6976	12 mos.

TABLE 4-12. GRIDDED TUBES - GROUPING BY AGE

STORAGE INTERVAL	AVG. AGE	UNITS	FAILURES	HOURS	ACTUAL λ IN FITS	PREDICTED λ IN FITS
1	1	87	4	.0635	62992	37384
2	2	62	3	.0905	33149	22283
3	3	63	3	.1380	21739	16463
4-5	4.5	72	1	.2360	4237	12183
6-7	6.5	76	7	.3584	19531	9286
8-9	8.4	70	4	.4271	9365	7662
10-12	11.3	81	5	.6694	7469	6109
13-16	14.5	76	2	.8059	2482	5072
17-22	19.5	70	3	.9965	3011	4071
23-33	27.7	74	3	1.4987	2002	3129
34-78	43.1	47	4	1.4783	2706	2252

$$\lambda(t) = e^{(.254-1)\mathrm{Ln}t - \mathrm{Ln}(1.0194)}$$

Index of Correlation = 0.85

t = Storage time in billion hours

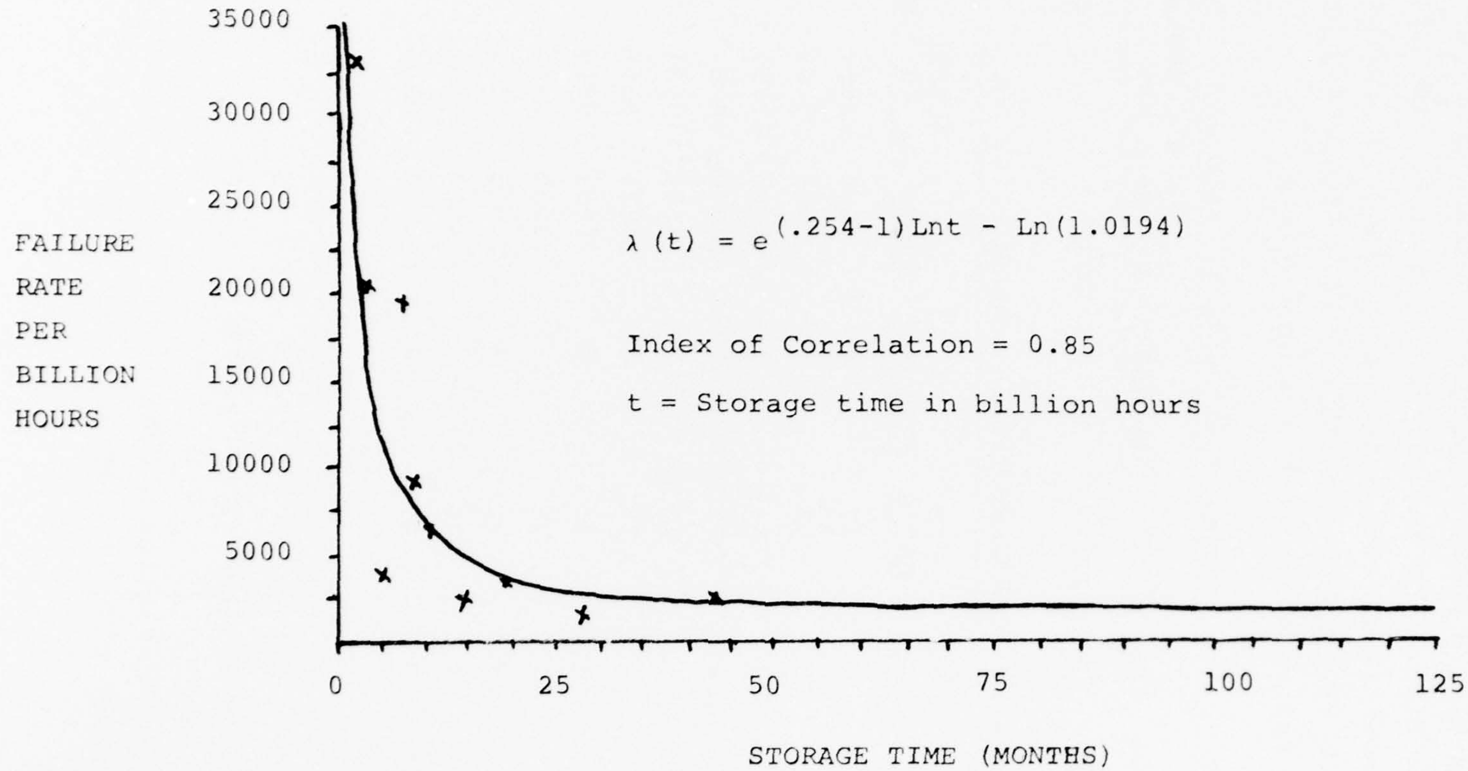


FIGURE 4-5. GRIDDED TUBE FAILURE RATE MODEL

4.2.5 AMPLITRONS

Only one data entry was available on amplitrons as shown in Table 4-13. The data was sorted by age into groups of approximately 24 units each showing a decreasing failure rate with time. A Weibull failure rate function was fit to the data as shown in Table 4-14. Figure 4-6 presents a graph of this function with the data points.

TABLE 4-13. AMPLITRON FAILURE RATE DATA SUMMARY

ENTRY. NOS.	HRS. x 10^6	FAILURES	λ IN FITS	90% ONE SIDED CONF. LIMIT- λ IN FITS	AVG. AGE
60	1.970	13	6599	10234	19 mos.

TABLE 4-14. AMPLITRON - GROUPING BY AGE

STORAGE INTERVAL	AVG. AGE	UNITS	FAILURES	HOURS	ACTUAL λ IN FITS	PREDICTED λ IN FITS
1-3 mo.	1.9 mo.	26	1	.0321	31153	44703
4-7 mo.	5.5 mo.	24	2	.0964	20747	17690
8-18 mo.	13.4 mo.	23	2	.2256	8865	8769
19-26 mo.	24.2 mo.	23	2	.4073	4910	5512
27-33 mo.	29.4 mo.	27	3	.5789	5182	4743
34-88 mo.	41.3 mo.	22	3	.6628	4526	3630

$$\lambda(t) = e^{(0.214-1)\mathrm{Ln}t - \mathrm{Ln}(.9854)}$$

Index of Correlation = .82

t = Storage time in billion hours

4.2.3 LOW POWER VERSUS HIGH POWER TUBES

A comparison of the low power tube data to the high power tube data was made. The comparison was based on age between the two data sources. For TWT's, Magnetrons and Gridded Tubes, tests indicated no significant difference between the low power and high power tubes.

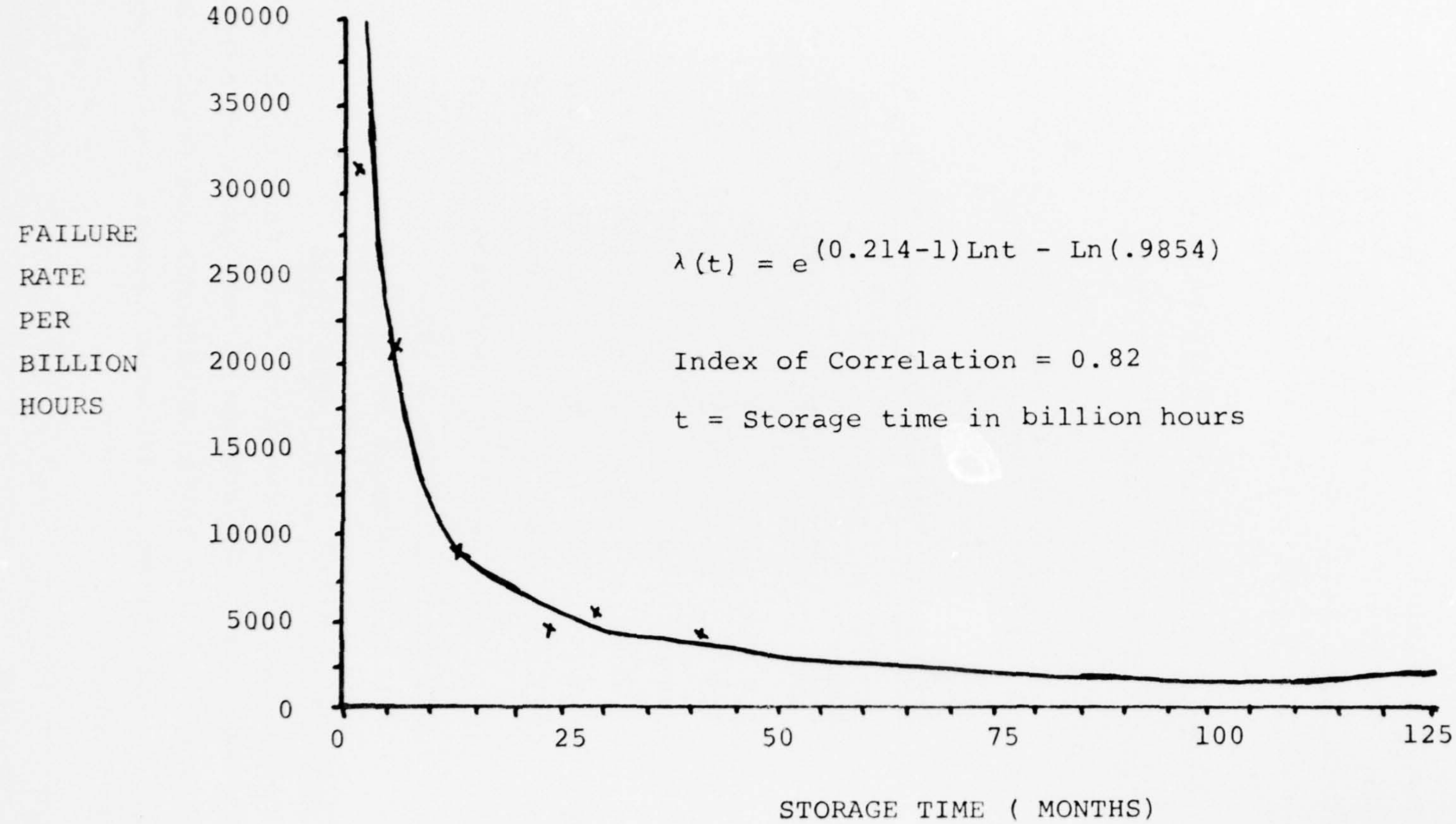


FIGURE 4-6. AMPLITRON FAILURE RATE MODEL

For the Klystron, the low power tube failure rate was significantly different from the high power tube.

4.3 NON-OPERATING FAILURE RATE PREDICTION

The failure rates models developed in the preceding analysis are presented in Figure 4-7.

4.4 ELECTRONIC VACUUM TUBE OPERATIONAL PREDICTION MODEL

The MIL-HDBK-217B failure rate model for electronic vacuum tubes is:

$$\lambda_p = \lambda_b \Pi_E \times 10^{-6}$$

where λ_b = base failure rate in million hours

Π_E = environmental factor

The values for these parameters are shown in Tables 4-15 and 4-16. The base failure is valid provided tubes are replaced before wearout.

FIGURE 4-7. ELECTRONIC VACUUM TUBE NON-OPERATING FAILURE RATE MODELS AND PARAMETERS

TUBE TYPE	FAILURE RATE MODEL	λ_b	α	β
Receiving	$\lambda = \lambda_b$	12	-	-
Klystron, Low Power	$\lambda = \lambda_b$	78	-	-
Klystron, High Power	$\lambda(t) = e^{(\beta-1)Lnt - Ln\alpha}$	-	1.0106	0.269
TWT, Low Power & High Power	$\lambda(t) = e^{(\beta-1)Lnt - Ln\alpha}$	-	1.0243	0.314
Magnetron, Low Power & High Power	$\lambda(t) = e^{(\beta-1)Lnt - Ln\alpha}$	-	1.0467	0.310
Gridded Tubes, Low Power, High Power	$\lambda(t) = e^{(\beta-1)Lnt - Ln\alpha}$	-	1.0194	0.254
Amplitrons	$\lambda(t) = e^{(\beta-1)Lnt - Ln\alpha}$	-	0.9854	0.214

λ = failures per billion hours   t = storage time in billion hours

TABLE 4-15. BASE FAILURE RATES FOR TUBES

TUBE TYPE	λ_b (f./10^6 hr.)
RECEIVER	
Triode, Tetrode, Pentode	5
Power Rectifier	10
KLYSTRON	
Low Power (e.g., local oscillator	30
High Power	
VA853	200
VA842	50
L3403	150
L3035	85
SAC42A	110
L3250	110
Z5010	190
ZM3038A	350
If high power type not included above:	
Peak Power <10 Megawatts	200
Peak Power $\geq$10 Megawatts	400
MAGNETRON	
Peak Power <10 Kilowatts	200
Peak Power $\geq$10 Kilowatts	450
TWT	
Peak Power <100 watts	30
Peak Power $\geq$100 watts, <10,000 watts	100
Peak Power $\geq$10,000 watts	200
CROSSED FIELD AMPLIFIER	
QK681	180
TRANSMITTING	
Triode	75
Pentode	100
CRT	15
THYRATRON	50

TABLE 4-16. ENVIRONMENTAL FACTOR FOR TUBES

ENVIRONMENT	G_B	S_F	G_F	A_I	N_S	G_M	A_U	N_U	M_L
Π_E	0.5	0.5	1.0	6.5	6.5	10	10	10	80

4.5 OPERATIONAL/NON-OPERATIONAL FAILURE RATE COMPARISON

Table 4-17 presents a comparison of operational and non-operational failure rates. The non-operational failure rates were calculated based on 10 years storage. The operating failure rates were calculated for a ground-fixed environment.

TABLE 4-17. OPERATING TO NON-OPERATING COMPARISON

TUBE TYPE	OPERATING FAILURE RATE (λ_{GF}) IN FITS	NON-OPERATING FAILURE RATE (λ_{NO}) IN FITS	RATIO $\lambda_{GF}/\lambda_{NO}$
Receiving	5000	12	4167.
Klystron, Low Power	30000	78	385.
Klystron, High Power	200000	915	219.
TWT, Low Power	30000	593	51.
TWT, High Power	200000	593	337.
Magnetron, Low Power	200000	602	332.
Magnetron, High Power	450000	602	748.
Gridded Tubes, Low Power	100000	1044	518.
Gridded Tube, High Power	180000	1044	172.

SECTION 5

CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

The primary storage failure mode for most types of high power vacuum tubes is loss of vacuum. Gridded tubes are the exception with the predominant failure mode being internal short.

There is not sufficient evidence to establish a relationship between storage failure rate and power or frequency. In fact, the data tends to indicate independence among those parameters.

There doesn't seem to be a difference in storage failure rate between pulsed and CW tubes. In all cases, pulsed and CW data were combined into a single failure rate.

In some cases, more than one failure rate was found for a particular class of tubes. Different failure rates were quoted when statistical tests indicated the likelihood of different populations within the data. The lack of definition regarding to tube manufacturing, storage conditions, quality grades and conditioning procedures did not permit a complete evaluation of these differences. These are believed to be the results of the combined effects of different manufacturing technologies, quality controls, storage environment, and tube conditioning procedures.

The storage data indicates that vacuum tube failures are occurring early in storage. Therefore, a decreasing failure rate has been predicted. The failure rate models assume that no tests are performed on the tubes in storage. Should the tubes be tested after a year, the failure rate should decrease significantly, since most of the failures should be removed as a result of the test.

Since loss of vacuum is the primary storage failure mode, proper conditioning of power tubes prior to operation would significantly increase the storage reliability.

5.2 Recommendations

To avoid gases to be trapped within the tube enclosure during manufacturing, tubes should be assembled in a high vacuum environment. Particular attention should be given to vacuum seals and to the selection of low porosity materials.

During storage, the humidity should be controlled to the maximum extent possible to avoid corrosion of external metal surfaces.

A large number of failures were attributed to handling and packaging. Special attention should be given to the design and construction of containers to avoid damage during transportation and handling.

Tubes equipped with vac-ion pumps should be pumped periodically to insure vacuum. The pump should always be operated prior to installation. Large tubes should be designed with a vac-ion pump.

Prior to full operation the tubes should be conditioned. The process should include as a minimum slow heater warm-up; anode, cathode and helix conditioning by applying high voltage gradually; and RF conditioning by applying RF drive gradually to maximum power level and pulse width.

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APPENDIX A

TEST OF SIGNIFICANCE OF DIFFERENCES IN FAILURE RATES (MORE THAN TWO POPULATIONS)

The storage reliability data is obtained from numerous sources. A detailed qualitative analysis is performed on the data to classify devices, environments, uses, quality levels, failures modes & mechanisms, and so on. Once the data sets are grouped according to these analyses, it is still not certain whether grouped sets of failure data are in truth from the same statistical population. It is possible that the failure rate characteristics of identical devices from the same manufacturers, with the same application, use environment, and so on, are not from the same population in terms of reliability -- possibly due to some problem on a production line for a certain lot or other factor.

Therefore a statistical test is performed to determine if the different data sets could be from the same statistical population.

The technique used is for more than two data sets and is taken from "Statistical Methods for Research Workers," R. A. Fisher, 13th edition, Hufner, 1963, pages 99-101.

The techniques assumes that the underlying failure distributions each have the same constant failure rate (λ). Therefore, the probability of a number of failures for each population can be represented by the Poisson distribution.

A single failure rate is calculated based on the pooled data sets being tested.

$$\lambda = \frac{\sum_{i=1}^{N} f_i}{\sum_{i=1}^{N} T_i}$$

where λ = Mean failure rate for all data sets

f_i = the number of failures in data set i

T_i = the total storage hours in data set i

n = the number of data sets being tested

The expected number of failures and the difference between the expected number of failures and actual failures is calculated for each data set based on the pooled data:

$$M_i = \lambda T_i$$

$$d_i = |f_i - m_i|$$

where

M_i = expected number of failures for data set: (based on the pooled data sets)

d_i = absolute value of the differences between the expected number of failures and the actual failures for data set i.

Next, lower and upper limits are calculated for the Poisson distribution:

$$U_i = [M_i + d_i] \text{ (if } U_i = f_i\text{, set } U_i = f_i - 1)$$

$$L_i = \langle M_i - d_i \rangle \text{ (if } L_i = f_i\text{, set } L_i = f_i + 1)$$

$$\text{(if } L_i < 0\text{, set } L_i = 0)$$

U_i = upper limit for data set i

L_i = lower limit for data set i

[ ] = rounded down to integer value

< > = rounded up to integer value

The probability that f_i failures would occur in data set i given the population failure rate is λ, is expressed by the Poisson distribution:

$$P_i = 1 - \sum_{j=L_i}^{U_i} P_{ij}$$

$$= 1 - \sum_{j=L_i}^{U_i} e^{-M_i} \frac{M_i^j}{j!}$$

The individual probabilities, P_i, are the significance probabilities for the individual distributions. It is required to test whether the ensemble of P_i taken together represents an improbable configuration under the null hypothesis which is that the underlying distributions have the same constant failure rate (λ).

The test is done as follows:

$$C_i = -2 \ln P_i$$

$$C = \sum_{i=1}^{n} C_i$$

Find Cr for $\alpha = .05$ (5% level of significance) and 2n degrees of freedom from the tables of chi square.

If C>Cr reject the null hypothesis (that all of the populations have the same failure rate.)

If the null hypothesis is not rejected, the data sets can be pooled and the common failure rate λ used.

If the null hypothesis is rejected, engineering and statistical analysis is required to remove data sets from the pooled data until the null hypothesis is not rejected.

EXAMPLE 1:

DATA SET	T_i	F_i	M_i	d_i	U_i	L_i	P_i	C_i
1	587.4	19	12.9	6.1	18	7	.0936	4.74
2	144.1	0	3.2	3.2	3	1	.0849	4.93
3	65.6	1	1.4	.4	2	2	1.000	0
4	95.8	1	2.1	1.1	3	2	.5406	1.23
5	128.	3	2.8	.2	3	3	1.000	0
6	281.	15	6.2	8.8	14	0	.0018	12.60
7	78.6	2	1.7	.3	1	1	1.000	0
8	484.8	0	10.7	10.7	21	1	.0016	12.93
	1865.6	41					ΣC_i =	36.43

pooled - λ = 21.98 fits

C = 36.43

2n degrees of freedom = 16

(from chi-square dist. at $\alpha = .05$) Cr = 26.30

Since C>Cr ---- the null hypothesis, that all of the populations have the same failure rate, is rejected.

EXAMPLE 2:

DATA SET	T_i	f_i	M_i	d_i	U_i	L_i	P_i	C_i
1	587.4	19	19.5	.5	20	20	1.0	0
2	65.6	1	2.2	1.2	3	2	.536	1.2
3	95.8	1	3.2	2.2	5	2	.277	2.57
4	128.	3	4.2	1.2	5	4	.641	.89
5	281.	15	9.3	5.7	14	4	.070	5.33
6	78.6	2	2.6	.6	3	3	1.02	.0
	1236.4	41						9.99

Pooled λ = 33.16 fits

C = 9.99

2n degrees of freedom = 12

$Cr = 21.03$

$C < Cr$ - accept null hypothesis --

All data sets have the same failure rate (λ = 33.16 fits).

APPENDIX B

ENVIRONMENTAL DESCRIPTION

Environment	Nominal Environmental Conditions
Ground, Benign	Nearly zero environmental stress with optimum engineering operation and maintenance.
Space, Flight	Earth orbital. Approaches ground, benign conditions without access for maintenance. Vehicle neither under powered flight nor in atmospheric re-entry.
Ground, Fixed	Conditions less than ideal to include installation in permanent racks with adequate cooling air, maintenance by military personnel and possible installation in unheated buildings.
Ground, Mobile (and Portable)	Conditions more severe than those for ground, fixed, mostly for vibration and shock. Cooling air supply may also be more limited, and maintenance less uniform.
Naval, Sheltered	Surface ship conditions similar to ground, fixed, subject to occasional high shock and vibration.
Naval, Unsheltered	Nominal surface shipborne conditions but with repetitive high levels of shock and vibration.
Airborne, Inhabited	Typical cockpit conditions without environmental extremes of pressure, temperature, shock and vibration.
Airborne, Uninhabited	Bomb-bay, tail, or wing installations where extreme pressure, temperature, and vibration cycling may be aggravated by contamination from oil, hydraulic fluid, and engine exhaust. Classes I and Ia equipment of MIL-E-5400 should not be used in this environment.
Missile, Launch	Severe conditions of noise, vibration, and other environments related to missile launch, and space vehicle boost into orbit, vehicle re-entry and landing by parachute. Conditions may also apply to installation near main rocket engines during launch operations.